Spatial Variations of Galaxy Number Counts in the SDSS I.: Extinction, Large-Scale Structure and Photometric Homogeneity

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ABSTRACT

We study the spatial variation of galaxy number counts using five band photometric images from the Sloan Digital Sky Survey. The spatial variation of this sample of 46 million galaxies collected from 2200 sq. degrees can be understood as the combination of Galactic extinction and large-scale clustering. With the use of the reddening map of Schlegel, Finkbeiner & Davis (1998), the standard extinction law is verified for the colour bands from u to z within 5% in the region of small extinction values, $E(B-V) < 0.15$. The residual spatial variations of the number counts suggests that the error of global calibration for SDSS photometry is smaller than 0.02 mag.

Subject headings: dust, extinction — cosmology: large-scale structure of universe — techniques: photometric

1. Introduction

The Sloan Digital Sky Survey (SDSS; York et al. 2000) is conducting photometric and spectroscopic surveys over about π steradians of the sky, producing a homogeneous data base of galaxies and other astronomical objects with accurate astrometric calibrations (Pier et al. 2002). The data published as *Data Release 1* (DR1; Abazajian et al. 2003; see also

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http://www.sdss.org/dr1/index.html) comprise 2196 sq. deg. of sky, which is about 25% of the survey goal. One of the most important features of the SDSS is its homogeneous photometry by virtue of a large format mosaic CCD camera (Gunn et al. 1998), and real-time calibration of the photometry using a 50 cm Photometric Telescope (Hogg et al. 2001).

In this paper we study the spatial variation of galaxy number counts observed in the photometric survey of the SDSS. The causes of the spatial variation are (i) spatial variation of extinction due to the dust in the Galaxy, (ii) large-scale structure of the Universe, and (iii) errors of photometric calibrations, especially those for stripe to stripe (or segments of stripes), since the observations are carried out along great circle scans (York et al. 2000). The prime motivation of the present work is to investigate (iii), but to acomplish this goal it is necessary to remove the effects of (i) and (ii), both which have fundamental scientific significance.

The most modern map of Galactic reddening over the sky is that of Schlegel, Finkbeiner & Davis (1998; SFD), which was produced by merging the COBE/DIRBE and IRAS/ISSA FIR maps. The extinction curve is given by $A_\lambda = k(\lambda)E(B - V)$, where $E(B - V)$ is the reddening. An important aspect of our study is to examine whether A_λ correctly describes extinction due to Galactic dust. The most model-independent test for the extinction correction can be made with galaxy number counts (e.g., Burstein & Heiles 1982). For this test, it is desirable to work with galaxy number counts as faint as possible, so that the galaxy density is sufficiently high and the distribution of galaxies is sufficiently smooth that large-scale clustering effects are small. We choose the range of magnitude as $r = 18.5 - 20.5$ mag (median redshift is 0.25), which is reasonably faint, yet photometric measurements are made at a high signal to noise ratio and the star-galaxy classification is hardly affected by the variation of seeing in the photometric survey in the SDSS.

Even at this faint magnitude we expect the effect of large-scale clustering to be appreciable. The importance of the effect, however, can be predicted from the angular two-point correlation function (Connolly et al. 2002).

The spatial variations in galaxy number counts that remain after subtraction of Galactic extinction and large-scale structure may be ascribed to variations of the photometric calibration, which is made stripe by stripe, or its segments when the scan of the stripe was obtained over several nights. The challenge is to separate these three effects, which we shall consider in this paper.

2. Galactic extinction

We show in Table 1 the data used in the present analysis. Stripes $\#9-12$ are the northern equatorial stripe ($\#10$) and neighbouring stripes, $\#82$ is the southern equatorial stripe, $\#76$ and $\#86$ are stripes in the southern sky, and the others are stripes in the northern hemisphere. The total area is 2196 sq. deg. We use the data processed with the photometric pipeline version v5.3, as given in DR1. We refer to Strauss et al. (2002) for the selection of galaxies from the photometric catalogue. The galaxy catalogue thus produced contains a small fraction of fake objects at bright magnitude $r' < 16$, but the contamination becomes negligible for fainter magnitudes which are considered in this paper; see Yasuda et al. (2001).

A survey stripe is 2.52 deg wide; scans can be up to 120 deg in length, and the stripe consists of a pair of TDI scan operations [denoted by (N,S) in Table 1] to fill the gaps between CCD chips. The imaging is made with the SDSS $ugriz$ filters (Fukugita et al. 1996). We work primarily with the r band data. We divide the stripe into square regions of 2.5 deg^2 along the stripes, and count galaxies contained in these square regions. The number of galaxies with $18.5 \leq r \leq 20.5$ mag contained in a square is approximately 11700; therefore the Poisson noise is about 0.4% (the corresponding magnitude offset, $\Delta m \simeq 0.004$ mag, is negligible for this work).

We first derive the differential number count $\overline{N}(m)$ from the entire sample employing the reddening map of SFD and the default standard extinction law (explained below). We then calculate the number count for each 2.5° square region without applying the extinction correction, and using the reference count curve $\overline{N}(m + \Delta m)$ with magnitude offset Δm, we fit it to the four data points in the range $r = 18.5 - 20.5$ mag devided into 0.5 mag bins by adjusting Δm with a chi-squares fit.

We show in Figure 1 Δm versus Galactic extinction, A_r^{SFD}, calculated from the reddening map of SFD assuming $k(r) = A_r/E(B-V) = 2.75$ from the standard extinction curve (SFD; O'Donnell 1994; see also Cardelli, Clayton & Mathis 1989; Fitzpatrick 1999) and calculating the mean of extinction over the $(2.5°)^2$ region. The individual data points and their binned mean in A_r^{SFD} are plotted. The error bars show the rms scatter. Although the scatter is significant, there is a clear trend that the mean of Δm and A_r are nearly identical, showing that the observed variation of galaxy counts is primarily due to Galactic extinction. Hence we may identify $\langle \Delta m \rangle = A_r^{\mathrm{counts}}$. Unfortunately, the scatter is so large compared to the fitting range of the abscissa that it is not possible to perform a two-parameter fit. So we first fit the data (using all data points) to determine the slope, enforcing that the curve passes through the origin (as the plot indicates), and then vary the constant while the slope is fixed. The fit yields $k(r')^{\mathrm{counts}} = A_r^{\mathrm{counts}}/E(B-V) = 2.64 \pm 0.11$ and the zero point that gives χ^2 minimum is 0.007 ± 0.005. The constant term is sufficiently small that it can be ignored.

The measured slope verifies the $k(r)$ from the standard extinction law together with the reddening map of SFD to an accuracy of 5%. The rms scatter around the line is 0.096 mag.

A similar analysis is made for the u, g, i and z colour bands. We selected the magnitude ranges of $18.5-20.5$ for u and g, $18.0-20.0$ for i and $17.5-19.5$ for z. The resulting plots are presented in Figure 2. The slope of the χ^2 fits and the dispersion around the curves as normalised by $k(\lambda)$ are summarised in Table 2. For all colour bands $k(\lambda)^{\mathrm{counts}}$ does not deviate from $k(\lambda)$ by more than $\approx$5%. Note, however, that our test is limited to the sky with small reddening of $E(B-V) < 0.15$ (the SDSS is designed to avoid high extinction fields; see York et al. 2000).

We may use $k(\lambda)^{\mathrm{counts}}$ to derive a constraint on the $R = A_V/E(B-V)$ parameter that represents total-to-selective extinction. The extinction curves of Cardelli et al. (1989) and their updates given by O'Donnell (1994) contain the parameter R $[R = k(V)]$ which is related to the greyness of the dust. Using O'Donnell's extinction curve, which is given by the form $A_\lambda/A_V = a_\lambda + b_\lambda/R$ with a_λ and b_λ functions of λ, we can derive constraint on R, for example $R = 2.98 \pm 0.23$ from the r-band. The constraints on R from other colour bands are given in Table 2. All constraints are consistent with $R = 2.8$ to 3.2.

Before we discuss the issue of the scatter around the relation, we examine the reddening in the colour of galaxies for a consistency check. Figure 3 shows $g - r$ colour of galaxies at the fifth percentile from the reddest as a function of $E(B-V)$ predicted by SFD. The trend of reddening against $E(B-V)$ is evident. The binned data points agree with the line $g - r = 1.04E(B-V)$+const., which is expected from the standard reddening law.

A further consistency test is given in Figure 4, where $\Delta m_g - \Delta m_r$ ($\langle \Delta m_g - \Delta m_r \rangle = (A_g - A_r)^{\mathrm{count}}$), which is derived from the extinction detected in the number count data, is plotted against $E(g - r)^{\mathrm{galaxy\ colour}} = (g - r)_{\mathrm{red\ 5\%}} - (g - r)_{\mathrm{red\ 5\%}}|_{E(B-V)=0}$ calculated from Fugure 3. The plot is consistent with $(A_g - A_r)^{\mathrm{count}} = E(g - r)^{\mathrm{galaxy\ colour}}$ (indicated by the dotted line), although the scatter is large and we see some data points that are scattered into the negative regions. Note that this figure shows a consistency of reddeing and extinction derived solely using the galaxy data, independent from the external data of $E(B-V)$ from Galactic far infra-red emission.

3. Spatial variations from large-scale structure

The rms scatter observed in the previous section is larger, by an order of magnitude, than that expected from the Poisson noise. To investigate whether the scatter is due to large-scale clustering of galaxies, we study the variation of galaxy counts in the r band varying

area sizes of sky regions.

We define circles with radii $r = 1.25°$ along the stripes, and decrease the radius keeping the centres of the circles fixed[6]. We count numbers of galaxies with $r = 18.5 - 20.5$ grouped into four 0.5 mag bins contained in those circular areas after applying an extinction correction according to the SFD map [assuming $k(r) = 2.75$], and then calculate the corresponding magnitude offset $(\Delta m)_c$ in the same way as above.

The rms scatter, $(\Delta m)_c$, thus obtained is plotted as a function the area $\Omega = \pi r^2$ in Figure 5. The error bars show the Poisson statistics. The rightmost point (open square) refers to the scatter observed in 2.5 deg square (6.25 sq. deg) which was seen in the previous section. We also added one more point for 3 sq. deg (open square) for comparison. (The data for square areas give values about $\approx$3% smaller than those for circular regions having the same area, as expected from the angular correlation function; see below.) The size of $(\Delta m)_c$ is larger than the Poisson noise at least by an order of magnitude. To study whether $(\Delta m)_c$, which increases as the area size decreases, can be attributed to the effect of large-scale clustering, we calculate the expectation from the empirical angular two-point correlation function $w(\theta)$. The fluctuations of the number of galaxies observed in area Ω are given by

$$\langle (N - \nu\Omega)^2 \rangle = \nu\Omega + \nu^2 \int_\Omega d\Omega_1 d\Omega_2 w(\theta_{12}), \tag{1}$$

where ν is the number of galaxies per unit solid angle. The rms of the count $\delta N/\overline{N} = \langle (N - \nu\Omega)^2 \rangle^{1/2}/\nu\Omega$ is translated to Δm using $\Delta m = (dN/dm)^{-1} \Delta N = (\alpha \ln 10)^{-1} \Delta N/N$ where $\alpha \simeq 0.42$ is the empirical slope of the count, $N \sim 10^{\alpha m}$, at the relevant magnitude range.

The angular correlation function estimated by Connolly et al. (2002) from the analysis for the northern equatorial stripe of the SDSS is

$$w(\theta) = A_w \theta^{1-\gamma}, \tag{2}$$

where $1 - \gamma = -0.722 \pm 0.031$ and $\log A_w = -2.13 \pm 0.13$ for $r^* = 19 - 20$ mag with the preliminary photometric calibration (Smith et al. 2002; Stoughton et al. 2002). This angular correlation function is consistent, within the errors, with earlier analyses (Stevenson et al. 1985; Maddox, Efstathiou & Sutherland 1990; Couch, Jurcevic & Boyle 1993). Connolly et al. could show the power law only for $\theta < 1°$. Maddox et al., showed that the correlation function shows a break at around 2-2.5° from thier APM data. We, therefore, model the

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[6]We prefer to use circles rather than squares for the simplicity to interpret the data in terms of angular correlation functions.

angular correlation function by a two-power law that breaks at 2°, with the second power slope $1 - \gamma \approx -2.1$ consistent with the APM result.

Figure 5 shows that the rms scatter of galaxy number counts in different parts of the sky after correcting for Galactic extinction is consistent with that which is expected from the angular two-point correlation function integrated over circular areas. This means that a significant scatter around the extinction fits of Figures 1 and 2 is produced by large-scale clustering of galaxies.

4. Homogeneity of the SDSS photometric calibration

We now investigate the residual spatial variation of galaxy number counts integrated over segments of the stripes (some of the runs are merged) given in Table 1. Figure 6 shows the offset after the extinction correction $(\Delta m)_c$ calculated from the galaxy counts for specific segments of the stripes relative to the reference count. The error bars represent the standard deviation expected from the two-power model of the angular correlation function with a cut-off at $\theta = 5°$ in the integral (1) over the rectangular region of the segment.

The figure shows that the mean still scatters by $\sim \pm 0.04$ mag, but the majority of the data are consistent with zero if we consider the variation expected from large-scale clustering, i.e., 19 out of 32 data points are within 1 σ, and the maximum deviation is 1.6 σ. This implies a null detection of photometric calibration errors. We may make this statement more quantitative by applying the statistics in the following way. We estimate the likelihood that the observed $(\Delta m)_c$ distribution is consistent with the Gaussian distribution of the dispersion $\sigma_{\rm eff} = \sqrt{\sigma^2 + (\delta m)^2}$, where δm represents the error, other than that from large-scale structure, that increases the dispersion. We then calculate the probability as a function of $\sigma_{\rm eff}$, and find that the probablity of the observed distribution being consistent with the Gaussian at 68% confidence level (1 σ) only when $\delta m < 0.019$ mag. This is taken as the upper limit on the error from photometry. This error meets the design requirement of the SDSS photometry; the global variation of the calibration error is no more than random errors of photometry.

We do not carry out similar analyses for other colour bands, since the evaluation of the angular two-point correlation is only available in the r bands. Table 2 displays the continuous increase of the rms scatter from the z to the u band. Since it is known that the photometric accuracy of the g, r, and i bands are comparable (DR1), we would ascribe this increase to increasingly stronger large-scale correlation in bluer bands. For the u band, random photometric errors (~ 0.04 mag) may also contribute to the rms scatter, but they

are smaller than the increase of the rms scatter we observed from the g to the u band.

In conclusion, we have demonstrated that the spatial variation of galaxy number counts are understood as the sum of Galactic extinction and large-scale clustering of galaxies. The analysis verified the validity of the SFD extinction map and the standard extinction law from u to z band within 5% in regions of small reddening $E(B - V) < 0.15$. We find that the R parameter lies in the range $2.8 - 3.2$ for the extinction curve of O'Donnell (1994). Finally we do not detect systematic errors in the global SDSS photometric calibration at least those in excess of 0.02 mag from run to run.

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Table 1: Stripes used for this analysis.

stripe	segments	run: (N,S) pairs
9	1	(1140,1231)
10 (N. eq. stripe)	3	(756,1239), (756+745, 752), (745+752)
11	2	(1907,1462), (1992+1458,1462)
12	4	(2126,2125+2247), (2126,2247)
		(2190,2247),(2190,1478)
34	1	(2137, 2131+2243)
35	3	(2076, 1895)
		(2076+1895, 1889+2075+2074+1896)
		(2299+2305, 2326+2328)
36	5	(1345,1331), (1345,1332)
		(2189+1345,2078+2134)
		(1345,2238), (2335,2248)
37	4	(1402+1450,1350), (1412,1350)
		(1412,2206), (1453,2207)
42	1	(1336,1339)
43	1	(1356,1359)
76	1	(1043,1035)
82 (S. eq. stripe)	1	(2738+2662,3325)
86	5	(1659,1737), (1659+1891+1740,1729)
		(1741,1729), (1893+1869,1729)
		(1869+1045,1729)

Table 2: The extinction functions obtained from the galaxy number counts and those from the standard extinction curve.

colour bands	u	g	r	i	z
standard extinction curve $k(\lambda)$	5.155	3.793	2.751	2.086	1.479
$k(\lambda)^{\mathrm{counts}}/k(\lambda)$	1.021	0.995	0.959	0.938	0.952
	±0.036	±0.041	±0.040	±0.048	±0.060
rms scatter	0.143	0.125	0.091	0.083	0.073
constraint on R	3.21	3.08	2.98	2.94	2.99
	±0.39	±0.30	±0.23	±0.24	±0.27

Fig. 1.— Magnitude offsets corresponding to the variation of galaxy number counts in 2.5 degree square fields plotted against mean extinction calculated from the SFD reddening map and the standard extinction curve A_r^{SFD}. Larger circles are the mean in bins of A_r^{SFD}, and the error bars show the rms. The solid line is the result of a χ^2 fit, and dotted line is the identical regression line $\langle \Delta m \rangle \equiv A_r^{\mathrm{counts}} = A_r^{\mathrm{SFD}}$.
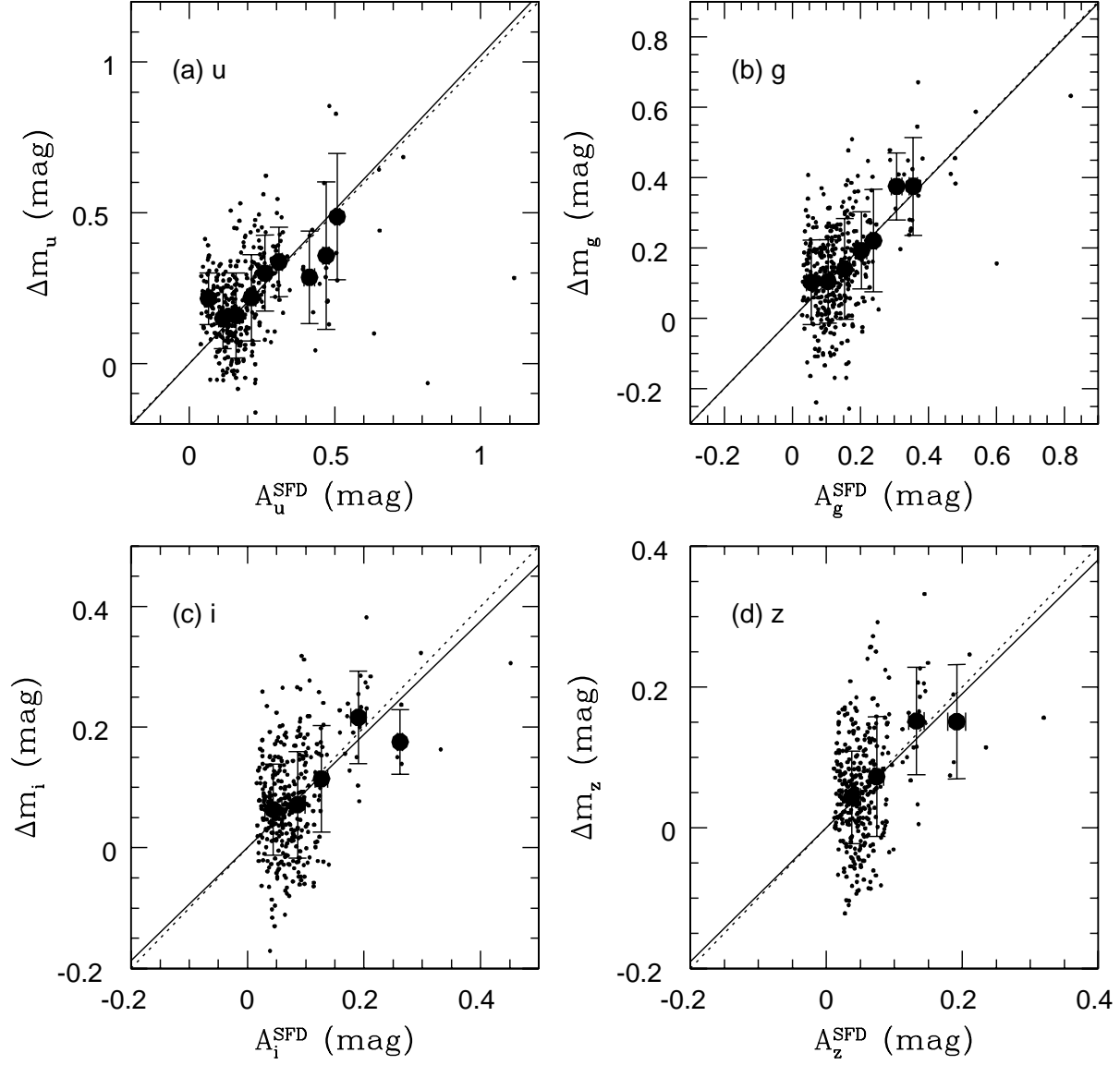
Fig. 2.— Same as Fig. 1, but for other four SDSS colour bands: (a) u band, (b) g band, (c) i band, and (d) z band.
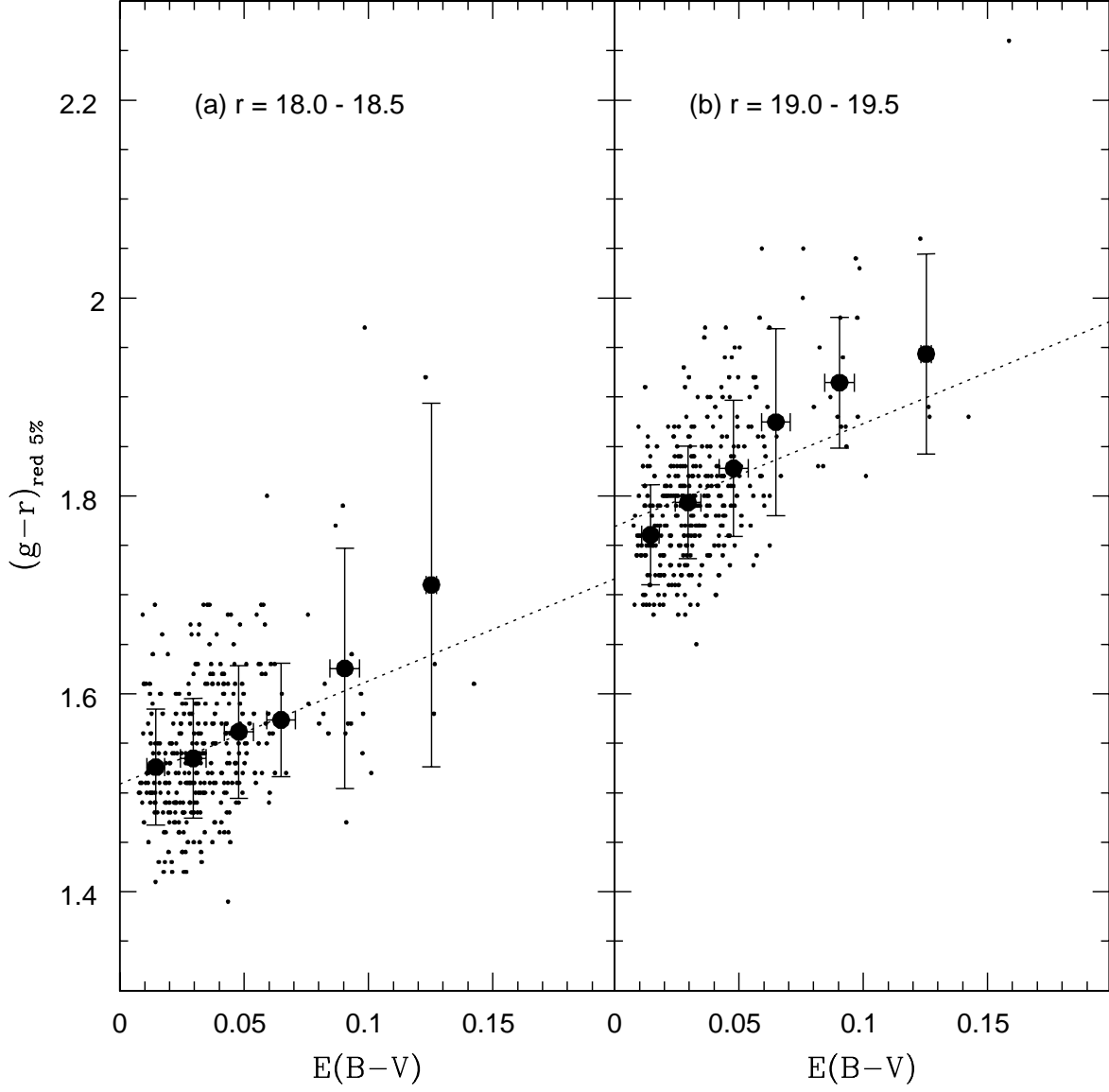
Fig. 3.— $g - r$ colours of galaxies at the 5th percentile from the reddest in 2.5 degree square regions plotted as a function of mean reddening obtained from the map of SFD. The figures are shown for two sets of galaxies (a) $r = 18 - 18.5$, and (b) $r = 19 - 19.5$. The lines represent $g - r = 1.04E(B - V)$+const expected for the standard reddening law.
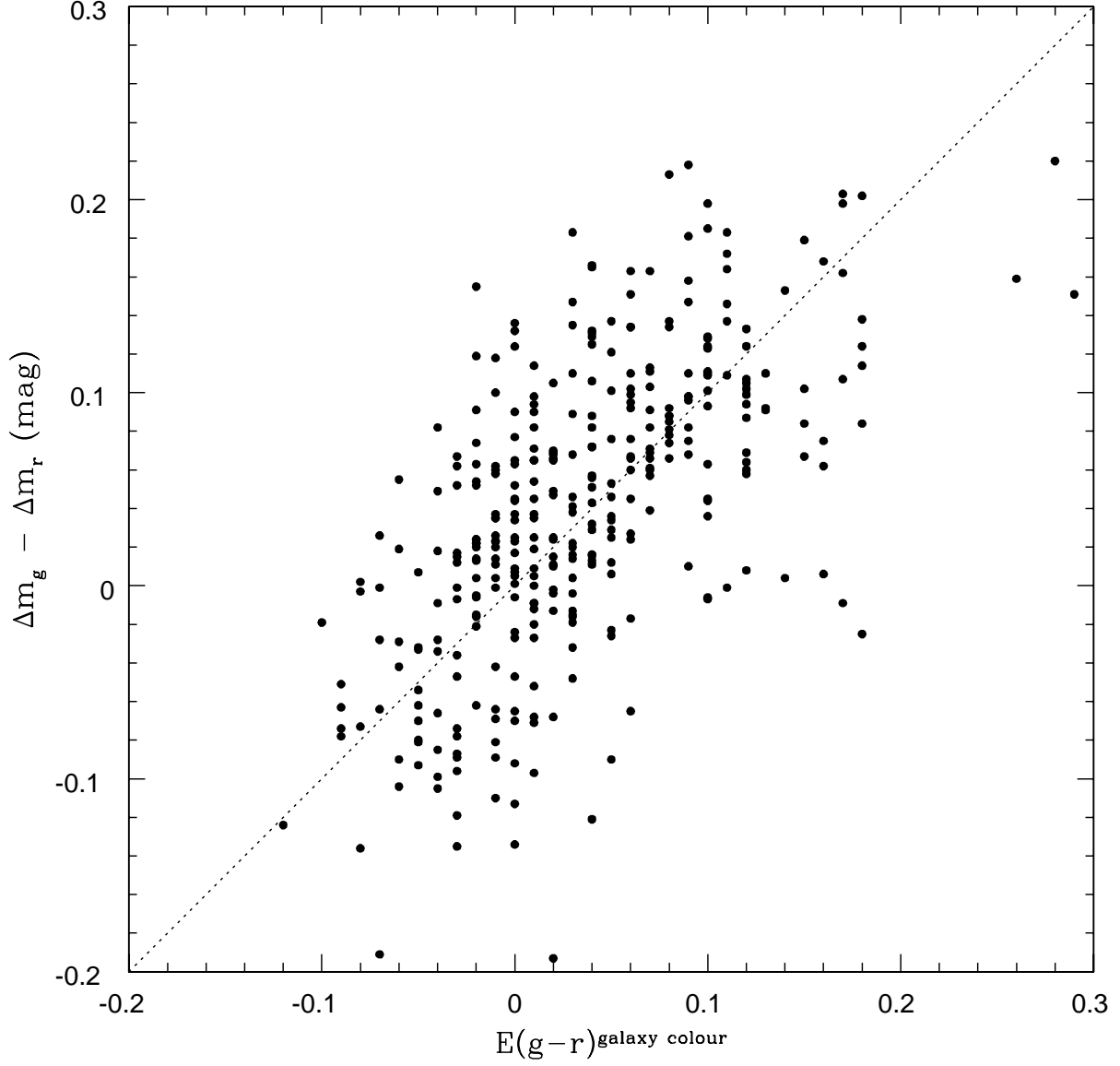
Fig. 4.— The difference of the offset of the number counts $\Delta m_g - \Delta m_r$, the mean of which is to be indetified with $(A_g - A_r)^{\mathrm{count}}$, plotted against $E(g-r)^{\mathrm{galaxy\ colour}}$ derived from the colour excess of galaxies. The dotted line shows the identical regression line $\Delta m_g - \Delta m_r = E(g-r)^{\mathrm{galaxy\ colour}}$.
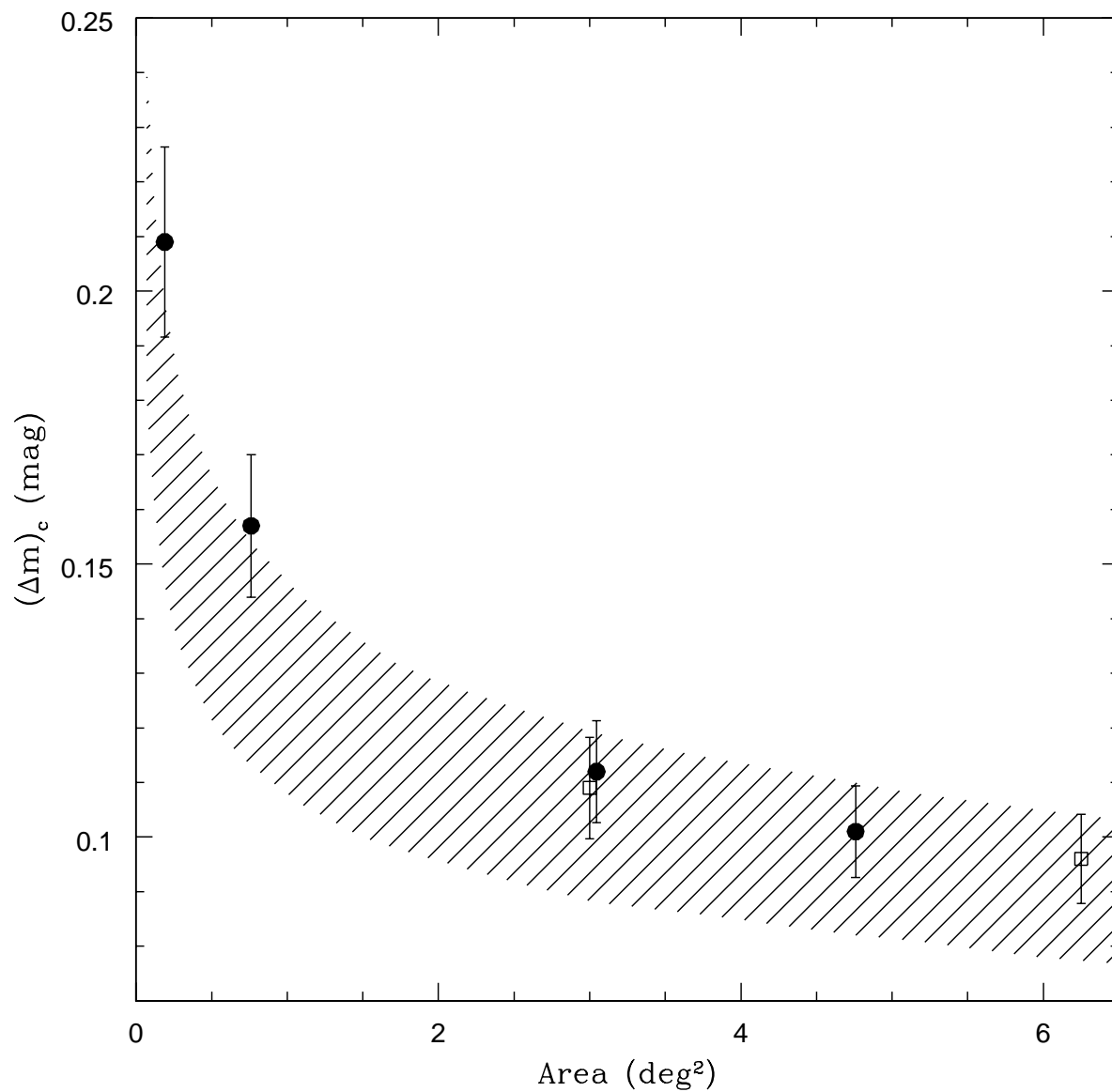
Fig. 5.— The excess of galaxy number counts (after applying the extinction correction) as a function of the area Ωr^2 represented as the offset of magnitude from the mean. The expectation from the angular two-point correlation function is represented by shading.
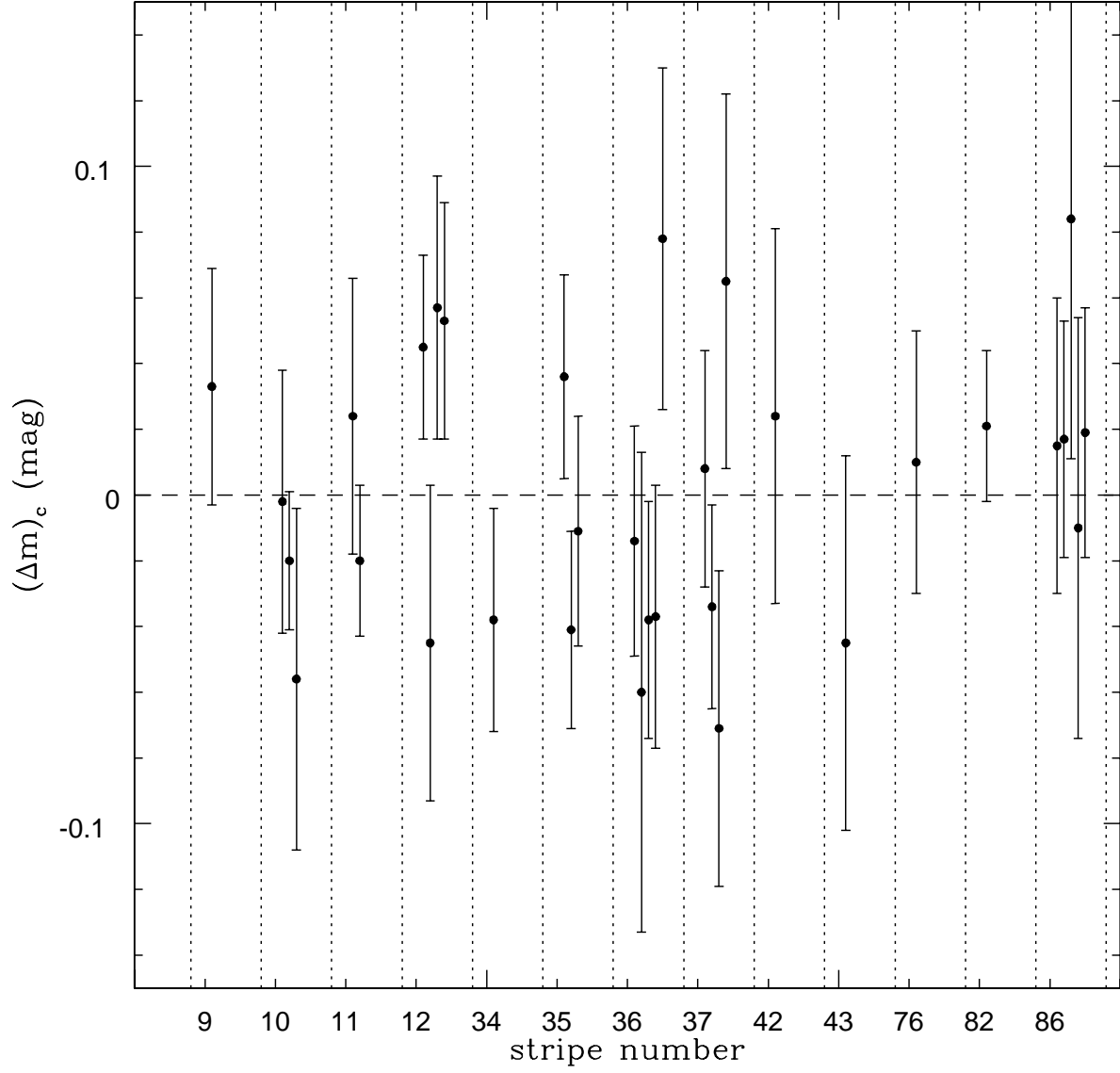
Fig. 6.— Magnitude offsets corresponding to the variation of galaxy number counts (after applying the extinction correction) integrated over the segment of stripes as defined in Table 1. The error bars represent the variation expected from large-scale clustering of galaxies. The abscissa is the stripe number.